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HST Observations of Black Hole X-Ray Transients

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Abstract. Hubble Space Telescope Observations of Black Hole X-Ray Transients are discussed in the context of the disk instability outburst model. We focus on the multiwavelength campaign following GRO J1655-40 through the summer 1996 outburst.

1. Introduction

As soon as the class was discovered, the obvious similarities between the Black Hole X-Ray Transients (BHXRTs) and their white dwarf analogues, dwarf novae (DN), guided investigations into the mechanisms responsible for the dramatic outbursts exhibited by the former. The outbursts in DN have been successfully explained as the result of temperature-dependent viscosity in the accretion disk: the Disk Instability Model (DIM) (Cannizzo 1993). The longer recurrence timescales for BHXRTs and the shapes and durations of their outburst lightcurves, however, provide a challenge to the DIM (Lasota 1996).

The DIM makes definite quantitative predictions for the temperature distribution, and hence the expected broad band spectrum, throughout the outburst cycle (*e.g.* Cannizzo, Chen, & Livio 1995). Accretion disk emission is likely to dominate in the UV, so one of the primary motivations for spectroscopic observations of BHXRTs with HST is, therefore, to observe the broad band spectral evolution, and hence address the question of the driving mechanism for the transient outbursts. This paper reviews the UV-optical spectra of BHXRTs obtained with HST, and describes the consequent deductions about the outburst mechanisms.

2. Observations of Individual Systems

2.1. A0620-00

The first BHXRT to be observed with HST was A0620-00, 16 years after the 1975 outburst. McClintock, Horne, & Remillard (1995) interpreted the $1100 - 4500$Å HST spectrum in conjunction with a quiescent ROSAT observation. After subtracting the contribution of the K5 V mass donor star, they found an optical-UV accretion spectrum which could be modeled as a 9000 K blackbody, with an area of only $\sim 1\%$ of the disk area. The low UV flux emitted by this accreting black hole was a surprise. By analogy with quiescent DN a mass transfer rate into the outer disk of $\dot{M}_{\rm disk} \sim 10^{-10}$ $M_{\odot}$ yr^{-1} was inferred. Meanwhile, the ROSAT soft X-ray flux implied a mass transfer rate through the inner disk of

only $\dot{\rm M}_{\rm BH} < 5 \times 10^{-15}$ $\rm M_\odot$ $\rm yr^{-1}$. Qualitatively, therefore, these findings were in agreement with the DIM, suggesting the accumulation of material in the quiescent outer disk. The extremely low $\dot{\rm M}_{\rm BH}$ seemed improbable, however, and the authors pointed out that isolated black holes might well accrete more than this from the ISM!

A new explanation was advanced by Narayan, McClintock, & Yi (1996), who postulated that the standard disk model is only applicable to the outer flow, and that within ~ 3000 $\rm R_{Sch}$ the flow is advective: *i.e.* the viscously-generated thermal energy is carried with the flow rather than being promptly radiated away. For black hole accretors, this advected energy can be carried through the event horizon. With this hypothesis, therefore, the extremely low quiescent accretion fluxes do not necessarily demand the extremely low mass transfer rates inferred from the standard accretion disk model.

2.2. X-Ray Nova Muscae 1991

This object was the first to be monitored in the UV-optical through the decline from outburst, though HST observations occurred only at one epoch, four months after the maximum. The spectral evolution was analyzed by Cheng et al. (1992). The data appeared consistent with steady-state optically thick accretion disks and the deduced mass transfer rate fell monotically during the decline. The DIM predicts, however, that the declining mass transfer rate is accompanied by a cooling wave propagating through the disk as successive hot, high viscosity, annuli make the transition to the cool, low viscosity, state. The consequent changing temperature distribution should have produced an observable cooling wave signature at the long wavelength end of the spectrum. The cooling wave was not observed, however, suggesting problems with the straightforward application of the DIM to BHXRTs.

2.3. GRO J1655-40

GRO J1655-40 was discovered in 1994 July; since then it has undergone repeated outbursts to a similar level and is apparently an atypical BHXRT. Superluminal radio jets were associated with the 1994 outburst (Hjellming, these proceedings). Following the onset of X-ray activity in April 1996, HST spectra were obtained on five separate visits from 1996 May 14 to July 22. A full description of these observations and the associated multiwavelength campaign is given in Hynes et al. (1997).

GRO J1655-40 is a highly reddened source, so an accurate correction for interstellar extinction is a prerequisite to any analysis of the spectrum. The 2175Å feature gives a sensitive measure of the extinction: E(B-V)=1.2 ± 0.1, a value consistent with direct estimates of the visual extinction and with measurements of interstellar absorption lines (Hynes et al. 1997).

Figure 1 is the 1996 May 14 dereddened UV-optical spectrum. Though the UV portion of the spectrum is consistent with the $\nu^{1/3}$ power-law predicted by the steady-state blackbody disk model, the optical ($\lambda > 2600$Å) spectrum rises to longer wavelengths in contrast to the predictions of the model. Ignoring the $\lambda > 2600$Å data, a $\nu^{1/3}$ model can be fit to the UV data, leading us to deduce the mass transfer rate is $1 \times 10^{-7}\ \rm M_\odot\ yr^{-1} \leq \dot{M} \leq 7 \times 10^{-6}\ M_\odot\ yr^{-1}$, where the dominant source of uncertainty arises from interstellar extinction. Taking a

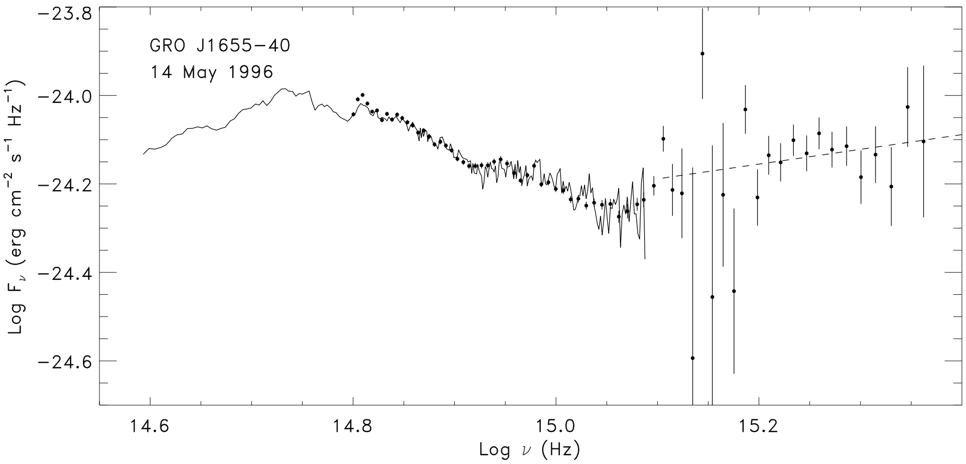

Figure 1. The dereddened spectrum of GRO J1655-40. The spectral slope changes dramatically at log $\nu \sim 15.05$ ($\lambda \sim 2600$Å). The dashed line shows a $f_\nu \propto \nu^{1/3}$ fit to the UV data.

compact object mass of $7\,M_\odot$ and assuming an accretion efficiency of 10%, the Eddington rate is $\dot{M}_{Edd} = 1.6 \times 10^{-7}\,M_\odot\,yr^{-1}$, so near the peak of the outburst this interpretation of the UV spectrum implies $\dot{M} \approx \dot{M}_{Edd}$.

We need to invoke something other than a pure steady-state optically thick accretion disk in order to explain the optical light. The shape of the spectrum is qualitatively suggestive of an irradiated disk; irradiation can alter the temperature profile of the outer disk producing a rise in flux towards longer wavelengths as illustrated in Figure 2. The multiwavelength lightcurves for the outburst (Hynes et al. 1997, and Hynes et al. these proceedings) do not, however, appear to support a simple irradiation model: the optical and UV flux declines while the X-ray flux rises!

In order to characterize the optical component of the spectra we fit blackbody spectra to the $\lambda > 2600$Å data for each visit (Figure 3). While the fluxes fell by about a factor of three between our first and last visit, the color temperature remained almost constant, dropping from 9800 K to 8700 K; the emitting area dropped from 5.0×10^{23} cm^2 to 2.2×10^{23} cm^2. The system parameters for GRO J1655-40 are well constrained (Orosz and Bailyn 1997, hereafter OB97, Hjellming and Rupen 1995) and the total available emitting area of the disk and secondary star is $\sim 5 \times 10^{23}$ cm^2, so it is possible to explain the optical emission at the peak of the outburst as thermal emission, but only if both the secondary star and the majority of the disk area have essentially the same isothermal temperature distribution. Attributing the $\nu^{1/3}$ UV component to a steady-state disk is not necessarily ruled out, as this requires only the hot inner regions of the disk.

In addition to the large isothermal area, there is a suggestion that our optical spectra are more strongly peaked than a single temperature blackbody, so we considered non-thermal mechanisms. Self-absorbed synchrotron emission from

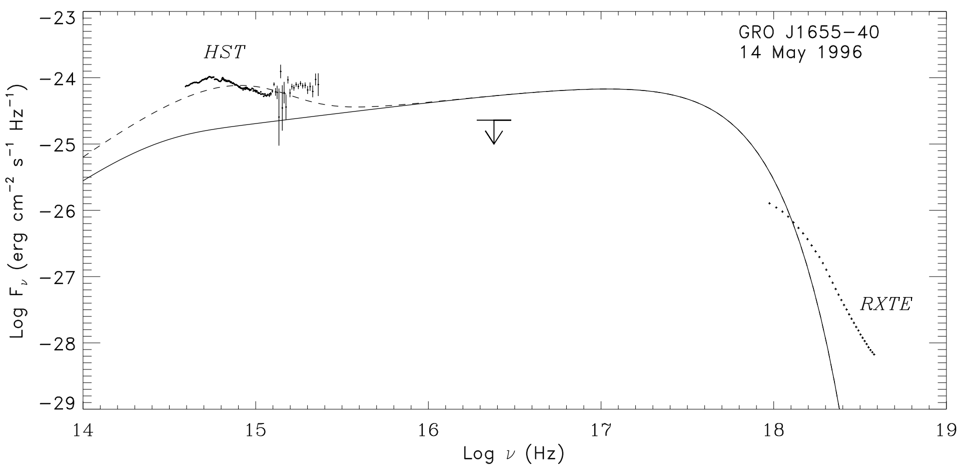

Figure 2. Composite spectrum for the May 14 observations. The solid lines shows a steady state accretion disk spectrum, whilst the dashed line shows an irradiated disk spectrum. These spectra are **not** fitted to the data, and are merely illustrative.

a cloud of relativistic electrons produced good fits to the optical component; the deduced electron energies are $\gamma \sim 60 - 90$, the magnetic field is B $\sim 40 - 60$ kG, and the size of the cloud is $50 - 100$ $\mathrm{R_{Sch}}$. Figure 3 shows both the blackbody and the synchrotron models. While the synchrotron models fit better, they have an extra free parameter.

Attributing substantial optical flux to this compact nonthermal source relieves the requirement for a large isothermal emitter in the system. It is interesting to note that intrinsic VRI band linear polarization ($> 3\%$) was detected in July 1996 (Scaltriti et al. 1997), consistent with the hypothesis of optical synchrotron emission.

On the other hand, the DIM may *require* a large isothermal outer disk for a long-period system like GRO J1655-40. Since the disk in such a system is large, the temperature for a steady state disk falls below the minimum temperature for the hot, high viscosity, state long before the outer disk is reached. Even for an Eddington mass transfer rate in GRO J1655-40 this limit is reached for a radius less than a quarter of the Roche lobe radius. This means that there is no global steady-state solution for $\dot{\mathrm{M}} \leq \dot{\mathrm{M}}_{\mathrm{Edd}}$. It is not clear what will happen to the temperature distribution in such a case, but it is possible that in outburst much of the outer disk could be maintained just in the hot state. Hence one might expect the outer disk to appear as an approximately constant temperature, shrinking area emitter as the decline proceeds. This hypothesis need to be tested with self-consistent numerical modeling, but until this is done our data cannot rule out a thermal interpretation.

The C IV 1550Å, Si IV 1400Å, and Si III 1300Å UV resonance lines shown in Figure 4 all show likely P-Cygni profiles. The peak to trough separation in all three cases is ~ 5000km s^{-1}, slightly larger than seen in outbursting dwarf

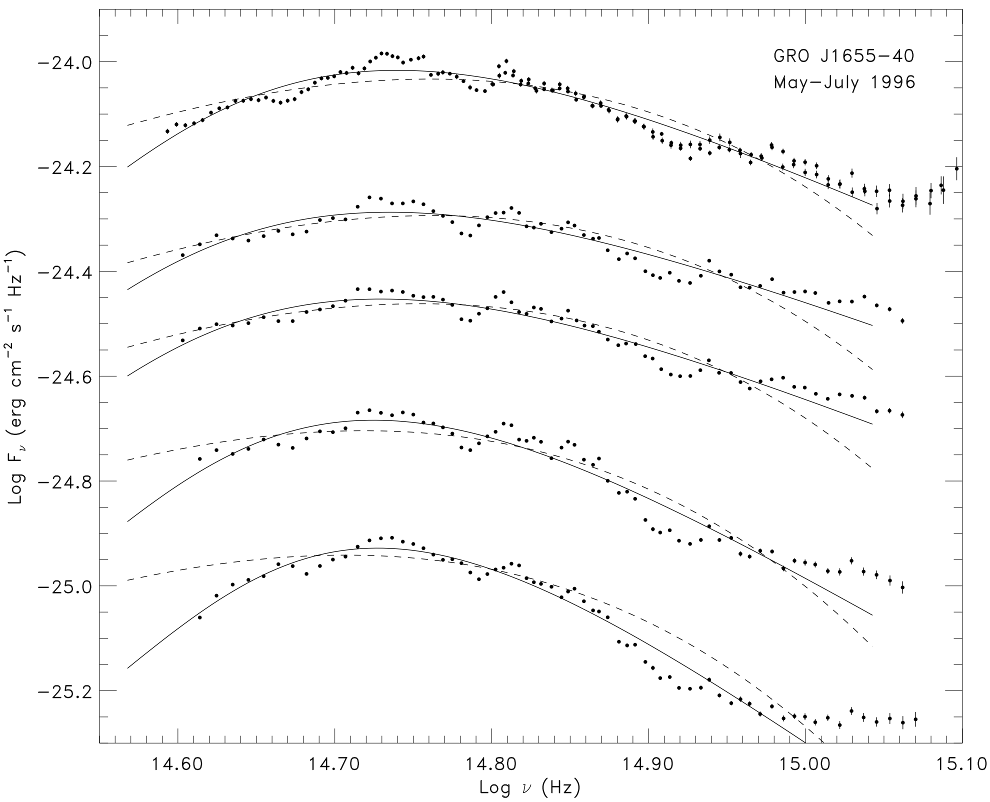

Figure 3. Blackbody (dashed line) and synchrotron (solid line) fits to the $\lambda > 2600$Å spectra. The bumps in the observed spectra are attributable to spectral line features in the source and to diffuse interstellar bands. In order to separate the successive visits clearly, a downward shift of 0.1 has been introduced in each visit relative to the one above it *i.e.* the lowest visit has been shifted downwards by 0.4.

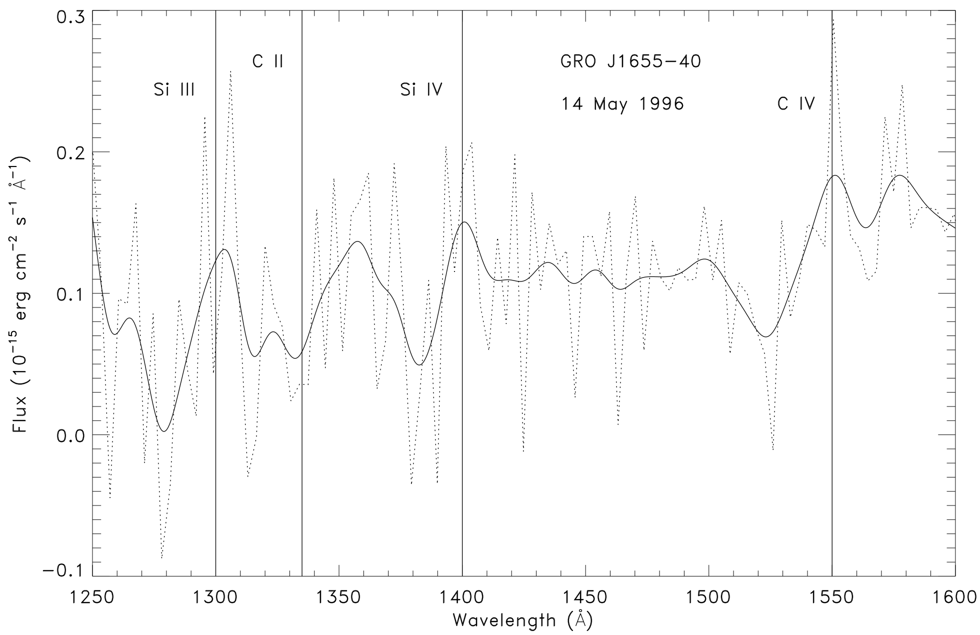

Figure 4. Likely P-Cygni profiles detected in the UV resonance lines

novae. Line profiles produced by biconical accretion disk winds were calculated by Shlosman and Vitello (1993) who found 'classical' P Cygni profiles only for inclinations around 60–70°, in striking agreement with the inclination determined for GRO J1655-40 (OB97). We conclude that there was likely a biconical accretion disk wind at the peak of the UV outburst, when $\dot{\mathrm{M}} \sim \dot{\mathrm{M}}_{\mathrm{Edd}}$.

2.4. GRO J0422+32

Observations of this target were obtained in early quiescence approximately two years after the first observed outburst, and seven months after the last reported reflare (Callanan 1995). A total of 4.6 hours exposure time was spent obtaining the optical-UV spectrum with five overlapping spectrograph set-ups. The target was extremely faint (R $\sim$ 21), so extreme care was taken with the data reduction. The spectrum is shown in Figure 5(a). We note that even if the entire 8000Å flux is attributed to the M2 V mass donor (Fillipenko, Matheson, and Ho 1995), the flux at 6000Å must be at least 50% due to the accretion flow, and shortwards of 5000Å the accretion light overwhelmingly dominates.

Shrader et al. (1994) obtained multiwavelength data in outburst, and noted that the optical-UV energy distribution showed a pronounced break in slope at 4000Å. E(B-V)=0.4 was deduced from the outburst IUE data. The quiescent HST data, dereddened using this value for the interstellar extinction, is shown in Figure 5(b).

The spectral shape in Fig. 5(b) is unusual. There is a very pronounced change in slope at $\sim$ 2600Å and the shape bears a strong resemblance to that of GRO J1655-40 in outburst (Figure 1.) By analogy with the synchrotron fits to

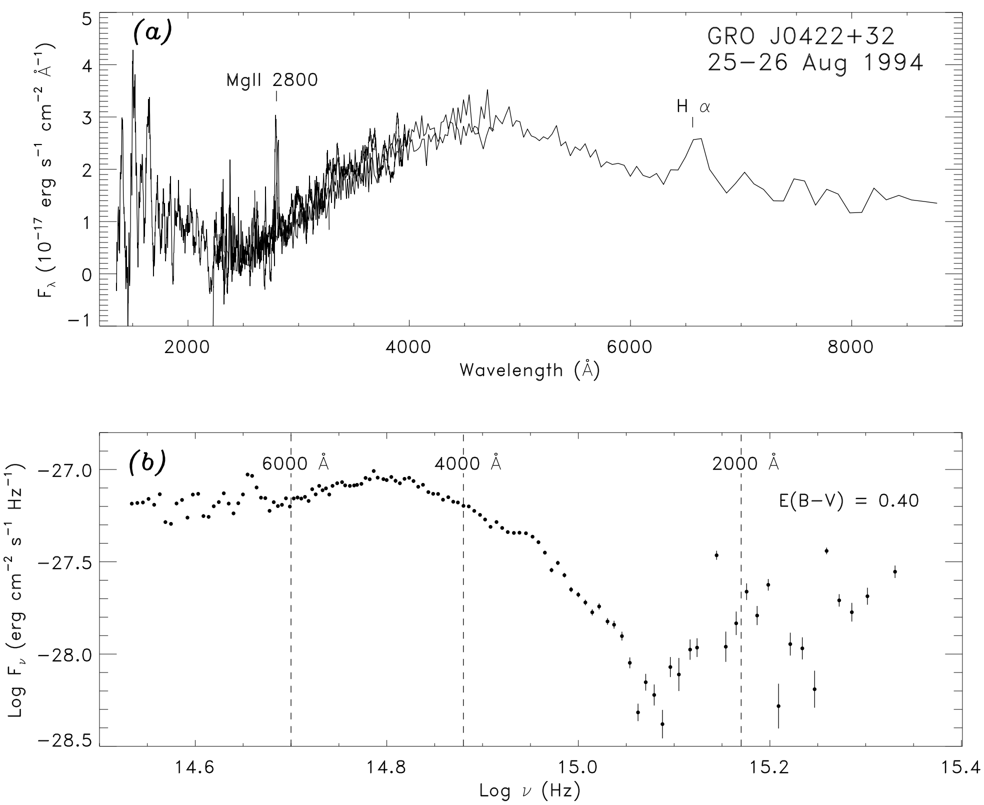

Figure 5. (a) The UV-optical spectrum of GRO J0422+32 in early quiescence. Much of the light at 8000Å is due to the mass donor star, but we are clearly detecting accretion flux at shorter wavelengths. (b) The spectrum dereddened using E(B-V)=0.4.

the GRO J1655-40 spectra, we speculate that the strongly rising optical accretion flux may be partly due to optical synchrotron as predicted by advection models (*e.g.* Narayan, Barret, & McClintock 1997).

3. Discussion and Future Work

The observations described herein have provided some intriguing challenges to the theoretical models for transient outbursts. As we collect detailed multi-epoch data on more systems it is becoming clear that the BHXRTs exhibit complex and diverse behavior, and it seems we need to consider a variety of mechanisms in order to properly understand the wealth of observational phenomena.

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